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Crop management and input optimization with GLYCIM: differing cultivars

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Abstract

The soybean simulation model GLYCIM is mechanistic and operates at the physical and physiological process level. The model is organized in modules along disciplinary lines using a generic modular structure. The model was initially validated with data sets collected at the Plant Science Farm at Mississippi State University and calibrated to the cultivar "Forest". In 1991 GLYCIM was released to soybean farmers and scientists at state experimental stations for crop management and input optimization. The soybean growers have claimed a 14–29% increase in yields and over a 400% increase in irrigation efficiency from using GLYCIM to manage irrigation. During the past two years, significant changes to GLYCIM have improved its predictions. Model improvements pertain to the effect of water stress on several physiological processes in the soybean plant and the method of accounting for numbers and weights of individual pods and seeds. In addition, cultivar parameter files have been developed for several cultivars. As a result of these changes, improved simulations have been obtained and grower usage of the model has been enhanced. The development of cultivar parameter files and the resulting simulations are discussed.

Keywords: Soybeans; Simulation models; GLYCIM soybean simulation model

1. Introduction

Crop simulation models are farm management tools capable of bringing new research information on crop physiology, genetics, soil science, entomology, and pathology from the scientist to the farmer in a quantitatively useful form. These models offer great potential for numerous improvements in crop production effi-

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ciency and crop management. New knowledge can arrive in a farmer's computer even before it is published in refereed research journals by using the models for research information transfer.

Crop simulation models can predict the growth of a crop from emergence to maturity, account for major physiological and morphogenetic processes, and describe the primary relationships in the soil-plant-atmosphere system. Models are being used for hypothesis testing and research planning. Model applications also include large-area yield forecasting, farm management decision making, breeding feasibility studies, and a large number of analytical studies. Charles-Edwards (1978) used simulation analysis to hypothesize about ways to improve crop productivity. The cotton simulation model, GOSSYM, was used retrospectively to study the reasons for yield decline in U.S. Cotton Belt between 1960 and 1984 (Reddy et al., 1989; Reddy and Baker, 1990). Since 1984 the cotton crop management system GOSSYM/COMAX has been used for input optimization, yield forecasting, and applications of growth regulators, harvest-aid chemicals, and insecticides in all the states of the U.S. Cotton Belt.

The soybean simulation model GLYCIM was developed by Acock et al. (1985) and was initially validated using data collected on cultivar "Forest" at the Plant Science Farm at Mississippi State University (Acock et al., 1985; Gertis, 1985; Aung, 1989). Since the 1991 growing season GLYCIM has been used by farmers for crop management and input optimization. The model is being used for selecting cultivar, row spacing, plant population and planting date prior to planting, and for post-planting decisions such as irrigation scheduling, insect control, harvest timing, and forecasting of final yield. The model helps farmers to optimize inputs, maximize profits, and minimize environmental pollution. In a recent survey by Mississippi State University, the soybean growers using GLYCIM with new cultivar parameters, for crop management reported a 14–29% increase in yields and a 400% increase in irrigation efficiency (Whisler et al., 1993).

Soybean growers are increasingly planting new cultivars and using GLYCIM for crop management. These cultivars differ in their response to various inputs from the Forest cultivar with which the model was originally developed and calibrated. It has become evident that, in order to use the model for maximum benefit to the growers and with better predictions for a range of cultivars and maturity groups, a set of cultivar dependent parameters are needed as input data. The objectives of the present study were (1) to identify physiological differences among cultivars for estimating parameters for GLYCIM, (2) to develop a universal soybean management system that will accommodate different cultivars and maturity groups grown under a range of environmental conditions.

2. Materials and methods

2.1. General description of GLYCIM

GLYCIM is a dynamic simulator of soybean crop growth that is mechanistic at the level of the physical and physiological processes involved in the transfer of materials in the soil, plant, and atmosphere. It is organized into modules in accordance with a generic modular structure and runs in hourly time steps. Documentation, including the FORTRAN listing, definition of variables, description of theory, and details of input and output files, has been published (Acock et al., 1985; Acock and Trent, 1991). Mechanisms involved in the physical and physiological processes in the plant and its environment were mathematically described in the model. These processes include light interception, carbon and nitrogen fixation, organ initiation, growth and abscission, and flows of water, nutrients, heat, and oxygen in the soil. All of the important factors known to influence these processes are included in the model along with information about how the factors interact. Carbon dioxide concentration in GLYCIM has a direct effect on gross photosynthetic rate and on photorespiration rate. Carbon dioxide concentration, both in the real plant and the model, has the potential to affect every aspect of plant growth and development. Carbon availability affects the expansion and dry weight gain of all the organs on the plant. Root growth influences water uptake, plant water relations, and stomatal conductance. Since the model was originally designed to examine the interactions between CO_2 and other environmental factors, all the processes in the model have been brought to approximately similar level of mechanistic detail.

The environmental inputs necessary to run GLYCIM are solar radiation, maximum and minimum air temperature, rainfall, and wind speed. The model also uses wet and dry bulb temperature if available. The program has the capability to use either hourly or daily environmental input data. GLYCIM also needs information on the physical and hydraulic properties of the soil, maturity group of the variety, latitude of the field, date of emergence, row spacing, plant population within a row, row orientation, irrigation amount, method and date, and CO_2 concentration of the atmosphere.

The model has been designed to simulate the growth of any maturity group on any soil and at any location and time of year. All soil processes in the model are mechanistic, and soil characteristics by horizon are required. Simulations are initiated at the cotyledonary stage with appropriate data on the number, size, and weight of organs on the plant. Plant growth in size and phenological stage are all predicted by the model. During simulation, the model provides predicted values for most of the physiological variables. It also simulates nitrogen concentrations of various organs on the plant and water and nitrogen status of the soil. The model provides the dry weights of all plant parts and final seed yield.

The generic modular structure of GLYCIM is presented in Fig. 1. The module SOILIN uses data on the characteristics and initial conditions of soil in the various horizons of the profile to calculate characteristics and initial conditions in each cell of the soil profile. The module WEATHER uses meteorological data and celestial geometry to calculate daylength, effective photoperiod, mean day and night temperatures, and hourly values of some environmental variables, including air temperature and vapor pressure deficit. The module LYTINT calculates hourly values of the total photosynthetically active radiation that would be intercepted by the crop canopy. Volumetric water content, water potential, hydraulic conductivity, oxygen concentration, temperature, and concentrations of ammonium and nitrate

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          ENVIRONMENTAL PROCESSES

SOILIN    INITIATE SOIL ENVIRONMENT
WEATHER   AERIAL ENVIRONMENT
              Celestial Geometry
              PAR & Diffuse Radiation
              Water Vapor Pressure
              Temperature
LYTINT    LIGHT INTERCEPTION
SOILEN    SOIL ENVIRONMENT
              Soil Water
                   plant uptake
                   evaporation
                   profile recharge
                   soil water potential
              Soil Nutrients
                   plant uptake
                   fertilizer additions
                   chemical transformations
                   leaching
              Soil Mechanical Impedance
              Soil Temperature
              Soil Oxygen

          PLANT PHYSIOLOGY

PHEN      STAGE OF DEVELOPMENT
PNET      CARBON FIXATION
              Photosynthesis
              Respiration
POTGRO    POTENTIAL GROWTH OF ORGANS
              Vegetative Shoot & Root
              Reproductive Organs
              Storage Organs
PARTIT    CARBON LIMITATIONS OF GROWTH
              Initial Carbon Partitioning
WATERS    WATER LIMITATIONS TO GROWTH
              Potential Transpiration
              Actual Water Uptake
              Leaf Water Potential
NUTRTS    NUTRIENT LIMITATIONS TO GROWTH
              Plant Nutrient Supply & Demand
              Distribution of Nutrients in Plant
ACTGRO    ACTUAL GROWTH OF ORGANS
              Vegetative Shoot & Root
              Reproductive Organs
              Storage Organs
TISLOS    TISSUE LOSS
SOYPLT    MORPHOLOGY
              Plant Geometry
```

Fig. 1. Proposed generic modular structure for plant simulators. Names of modules are capitalized. Subdivisions of modules are in upper/lower case.

in each cell in the soil profile are calculated in SOILEN. The vegetative and reproductive developmental rates are calculated in module PHEN. PNET uses single-leaf photosynthetic characteristics to calculate crop canopy characteristics and canopy gross photosynthetic rate. Photorespiration rate and maintenance respiration rate are calculated and subtracted to get net photosynthetic rate, which is corrected for stomatal closure caused by water stress. The net carbon fixation rate and the rate of carbon translocation out of the leaves are also calculated in PNET. The module POTGRO calculates potential rates of growth for all organs on the plant at a given air temperature assuming that carbon, water, and nutrients are plentiful. PARTIT calculates an initial partitioning of carbon to various organs based on priorities that change with stages of growth. WATERS maintains a functional balance between root and shoot by growing roots as necessary to meet transpiration demand. It calculates potential root water uptake for a number of key shoot water potentials and compares these with the potential transpiration rate to estimate shoot water potential. Depending on shoot turgidity, the shoot or root, or both, may grow. Stomatal conductance is a function of shoot turgidity.

2.2. Field data

Data were collected on several cultivars grown in farmers' fields in the Mississippi Delta with various soil types, weather scenarios, and management conditions during 1991–1993. These data represent over 20 crop years with varying planting dates, maturity groups, row spacing, plant density per meter row, and management inputs. At the time of germination, plots were laid out for destructive and non-destructive sampling with four replications. Throughout the season, control practices were employed to avoid any significant weed, insect, or disease problems.

Plant height, and vegetative and reproductive stages were measured non-destructively at weekly intervals. Twice during the season, dry matter accumulation of plant parts was measured destructively. Samples were selected at random, and the sampling unit consisted of a single 1-meter row from each plot, with four replications. Yield was recorded from the total area of the grower's field representing the same soil type and management practices. Cultivar parameter files were developed by simulating these crops.

In this study, GLYCIM was run using weather, soils, water, and management inputs for several cultivars. Where discrepancies between the real and simulated plant data occurred, the appropriate functions or parameter values were changed. The resulting changes in model parameters are compiled in the cultivar parameter files.

3. Results and discussion

The cultivar parameter file contains 18 parameters called PARM1–PARM18, mostly multipliers with initial value 1.0. The differences in growth and developmental rates of soybean cultivars can be generalized in the following broad groups: differences in rate of vegetative node production (PARM1, PARM2, PARM16), differences in the rates of progress through reproductive stages between R0 to R8 (PARM3, PARM4, PARM5, PARM6, PARM7, PARM8, PARM9, PARM10), differences in the rate of stem extension (PARM11, PARM12), and differences in dry matter partitioning (PARM13, PARM14, PARM15, PARM17, PARM18). The cultivar parameters were developed for several cultivars, but only a few of these parameters had to be changed to simulate growth, development, and yield for each. The cultivar parameters are incorporated in the equations as follows, and the variables are defined in the appendix.

In GLYCIM hourly increments in node addition are calculated as a function of air temperature during that period as follows:

$$PDV = ((0.018 * TAIRL - 0.11)/24.0) * PARM2$$

Progress towards R0 (floral induction) is calculated using the following equations, depending on the day of the year:

```
IF (JDAY .LT. 173)
    DR = 1/(35.0 * (PHOTO - DIFIMG * *1.46)/24 * PERIOD
ELSE
    DR = 1/(9.0 * (PHOTO - DIFIMG) * *1.31)/24 * PERIOD
ENDIF
DR = DR * PARM3
```

Rate of growth from R0 to R1 (Fehr and Caviness, 1977) is calculated as follows:

```
DR = (0.018 * TAIRL - 0.11)/RLEAF/24. * PERIOD * (1.0 - SGTLI)
DR = DR * PARM4
```

Progress of reproductive development from R1 to R2 is calculated as a function of water stress as follows:

```
DR = PDR * PARM5 * PERIOD * (1.0 - SGTLI)
```

Progress from R2 to R3 is calculated using similar functions as floral induction:

```
IF (JDAY .GE. 173) THEN
    PDR = 1.0/(2.0 + (9.0 * (PHOTO - DIFIMG) * *1.31))/24.0
ELSE
    PDR = 1.0/(2.0 + (35.0 * (PHOTO - DIFIMG) * *1.41))/24.0
PDR = PDR * PARM6
```

Rate of growth between R3 and R4 is a function of photoperiod:

```
PDR = (1.0/((1.2 * PHOTO) - 6.0)/24.0) * PARM7
```

The seed-filling phase of reproductive growth is calculated as a function of seed-fill rate, which depends on source sink relations:

```
IF (RSTAGE .LT. 6.0) THEN
    RSTAGE = 4.0 + (SDFILL * 2.7) * PARM8
IF (RSTAGE .LT. 7.0) THEN
    RSTAGE = 6.0 + ((SDFILL - 2.0/2.7/PARM8) * 4.0) * PARM9
```

The potential rate of change in stem extension rate is a function of the number of mainstem nodes and physiological stress:

$$\mathrm{PDMH} = (\mathrm{PARM11} + (\mathrm{PARM12} * (\mathrm{VSTAGE} + \mathrm{PDV}/2.0) * *1.37)) * \mathrm{PDV} * \mathrm{SLOW}$$

The rate of dry matter distribution to stems, petioles, and roots is calculated as follows:

$$\mathrm{PDMW} = (\mathrm{PDMH} * \mathrm{PARM14}) + (8.7\mathrm{E}{-5} * (\mathrm{PDMH} * \mathrm{PDMH} + (2.0 * \mathrm{PDMH} * \mathrm{MSTEMH})))$$

$$\mathrm{PDPWM(I)} = (\mathrm{PDPLM(I)} * \mathrm{PARM17} + (8.7\mathrm{E}{-5} * (\mathrm{PDPLM(I)} * \mathrm{PDPLM(I)} + (2.0 * \mathrm{PDPLM(I)} * \mathrm{MPETL(ITRIF)}))))$$

$$\mathrm{PDWR(L, K)} = \mathrm{RTWT(L, K)} * \mathrm{PARM18} * \mathrm{RGCF(L, K)}/24.0$$

The maximum number of mainstem nodes that can be produced after floral initiation is calculated as a function of existing mainstem nodes on the plant:

$$\mathrm{VSTMAX} = \mathrm{IFIX}(8.0 * \mathrm{VSTAGE} * *\mathrm{PARM16})$$

We had no prior knowledge of the exact parameter changes that would be needed for the model to simulate the performance of the crop represented by the plant height, vegetative, and reproductive stages. We therefore made several changes to the parameters and repeatedly ran GLYCIM, removing one at a time any unnecessary parameter changes we had in the parameter file. After repeated simulations, we determined the final necessary parameter changes for each of the cultivars (Table 1). If a cultivar is grown in more than one soil type or weather conditions, the second crop is used to test the validity of the cultivar file.

With these parameter changes, GLYCIM simulated the seasonal changes in plant height, vegetative stages, and reproductive stages for all the cultivars presented in Table 1. The observed data and simulations for cultivar DPL 415, grown in Sharkey silty clay soil, are presented in Fig. 2. The simulated and observed data for plant height were very close except at the end of the season, where the simulated height was higher than that for the observed data. The simulated vegetative and reproductive stages for this variety and final seed yield were very close to those of the observed field data (Fig. 2).

The data for cultivar NKS 5960, grown in Dundee loam and Sharkey clay loam soils, are presented in Figs. 3 and 4, respectively. The GLYCIM simulations were very close to the observed data on plant height, vegetative and reproductive stages, and final yield. The only slight discrepancy for this cultivar was in the simulation of late-season plant height, where the simulated height continued to increase at a higher rate than that in the observed data.

The cultivar Pioneer 9593 was grown in Dundee loam soil. GLYCIM simulation followed the observed data for all the plant parameters measured, and the final yield

Table 1
Cultivar-dependent parameters for GLYCIM

Parameter	Standard parameter	Cultivar/soil type						
		Asgrow 5979/ Dubbs 7, Sharkey 8	Pioneer 9501/ Dundee 19	Pioneer 9593/ Dundee 18, Sharkey 8	NKS 5960/ Foresdale 6, Sharkey 11, Dundee 14	Terravig 515/ Ora2ss	Hutcheson/ Sharkey 7	DPL 415/ Sharkey 9
PARM 1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PARM 2	1.0	0.6	0.8	0.6	0.6	0.8	0.5	0.8
PARM 3	1.0	1.0	1.4	1.3	0.8	0.7	0.6	0.6
PARM 4	1.0	1.2	1.2	1.0	1.0	0.9	1.0	1.0
PARM 5	1.0	1.2	1.2	1.0	1.0	0.9	1.0	1.0
PARM 6	1.0	1.2	1.0	1.2	1.0	0.9	1.0	1.0
PARM 7	1.0	1.0	1.0	1.2	1.0	1.0	1.0	1.2
PARM 8	1.0	1.0	1.0	1.0	1.0	0.8	1.5	1.4
PARM 9	1.0	1.0	1.0	1.0	1.0	0.5	1.2	1.2
PARM10	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PARM11	2.0	1.5	2.0	1.5	2.0	2.0	2.0	1.4
PARM12	0.23	0.2	0.23	0.22	0.20	0.23	0.23	0.23
PARM13	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
PARM14	0.007	0.007	0.007	0.006	0.007	0.007	0.007	0.014
PARM15	1.0	2.0	1.0	1.5	1.0	1.0	1.2	2.0
PARM16	0.38	0.17	0.38	0.24	0.25	0.38	0.20	0.2
PARM17	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0042	0.0024
PARM18	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.3

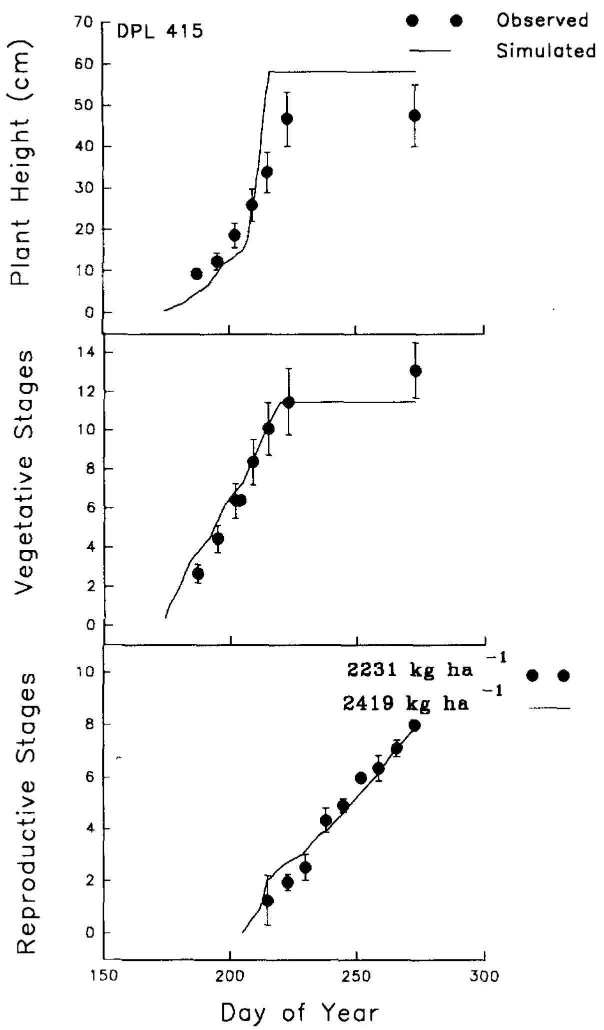

Fig. 2. Comparison of simulated and observed seasonal development of plant height and vegetative and reproductive stages for soybean cultivar DPL 415 grown in Sharkey silty clay soil in the Mississippi Delta.

was within one standard error of the observed data (Fig. 5). In this case, even the end-season simulated plant height was very close to that in the observed data. We also observed another cultivar, Asgrow 5979, grown in two soil types during 1992 and 1993. The simulations with the same cultivar parameter file were very close to the field-observed data for both years (Table 1 and Fig. 6).

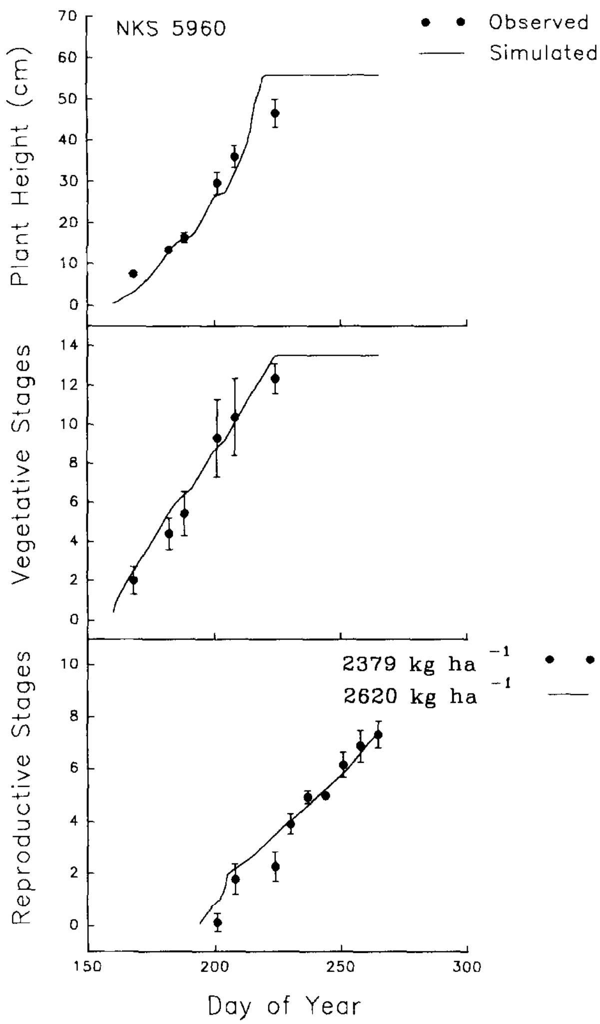

Fig. 3. Comparison of simulated and observed seasonal development of plant height and vegetative and reproductive stages for soybean cultivar NKS 5960 grown in Dundee loam soil in the Mississippi Delta.

3.1. Model application and impact

With the development of cultivar parameter files and an intuitive graphical interface for GLYCIM, both farmers and scientists are using the model for input optimization (Whisler et al., 1993; Remy, 1994). The model with cultivar parameter files provide soybean farmers with a new tool for selecting cultivars, planting time, and soil type for maximum yield. The growers using the model have indicated that yields increased by 10 to 29% and irrigation efficiency increased by 400% (Whisler et al., 1993; Remy, 1994). The farmers indicated, "By using the model's historical

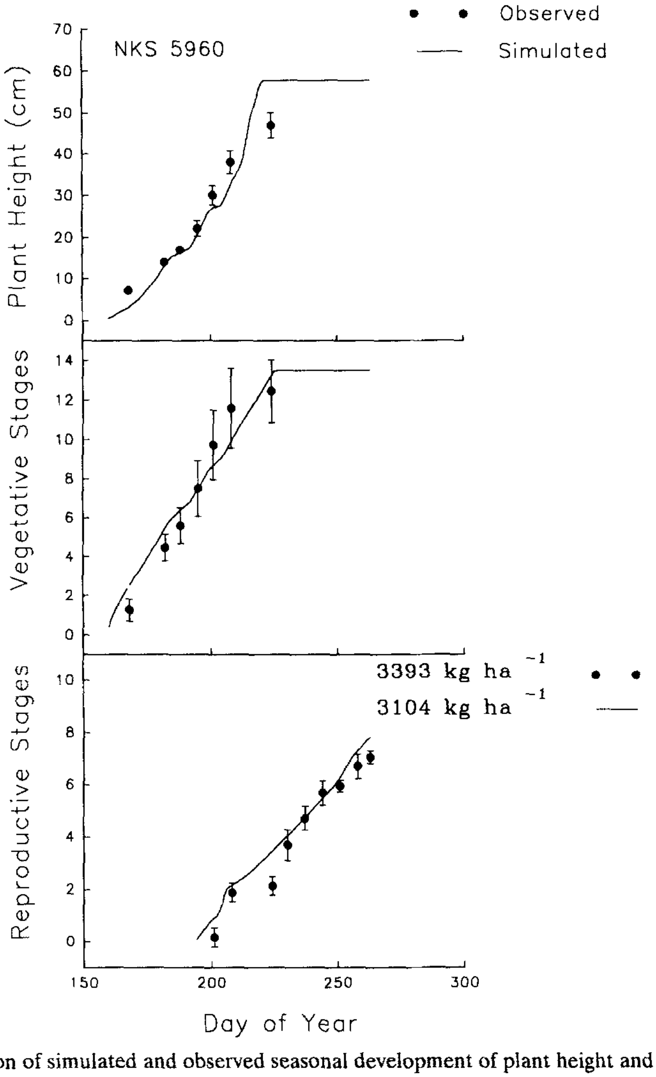

Fig. 4. Comparison of simulated and observed seasonal development of plant height and vegetative and reproductive stages for soybean cultivar NKS 5960 grown in Sharkey clay loam soil in the Mississippi Delta.

weather data and soil classification information, we can use GLYCIM to make pre-season decisions for the best varieties for various soil types, best row spacing for maximum yield, optimum number of seeds per foot of row, optimum planting dates, highest projected yields based on the criteria, and projected harvest dates" (Remy, 1994, p. 2). The farmers have also indicated that the in-season decisions such as time and amount of irrigations can be done more precisely for maximum yields with lower costs and reduced groundwater pollution (Remy, 1994). In addition, with the new cultivar parameter files, GLYCIM can be used to study the effect of climate change on soybean production and yield potential for many of these cultivars.

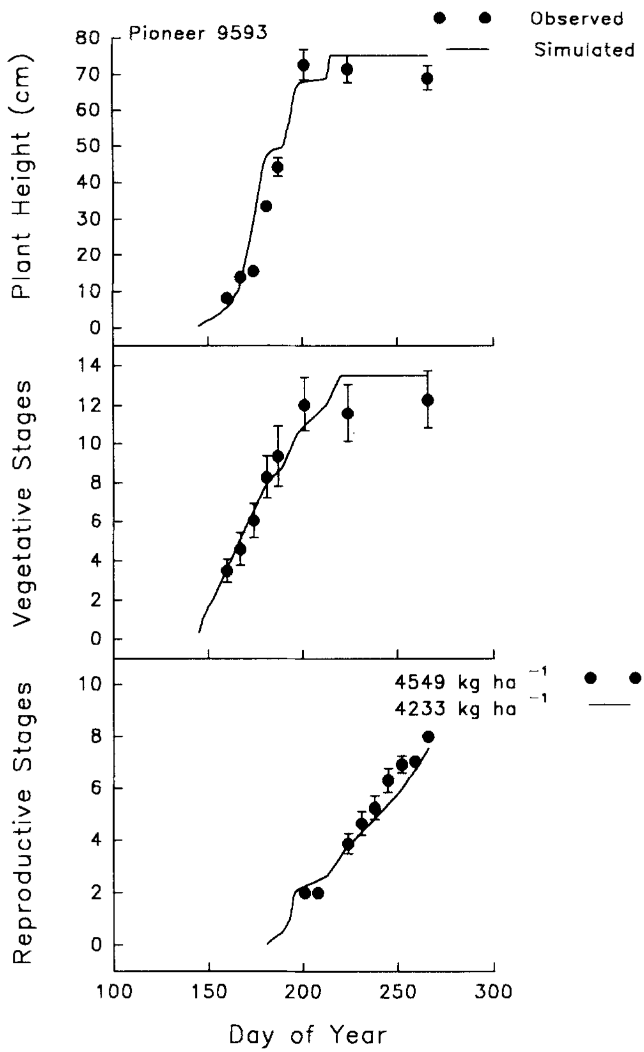

Fig. 5. Comparison of simulated and observed seasonal development of plant height and vegetative and reproductive stages for soybean cultivar Pioneer 9593 grown in Dundee loam soil in the Mississippi Delta.

Appendix: a dictionary of variables

DIFIMG:	Maximum daylength for immediate floral induction (hr)
DR:	Increment in reproductive stage for the period (RSTAGES hr^{-1})
ITRIF:	Trifoliolate leaf number on axis
JDAY:	Day of the year
MPETL(I):	Length of mainstem petiole bearing trifoliolate I (cm)
MSTEMH:	Mainstem height above cotyledonary node (cm)
PARM1... PARM18:	Cultivar-dependent parameters

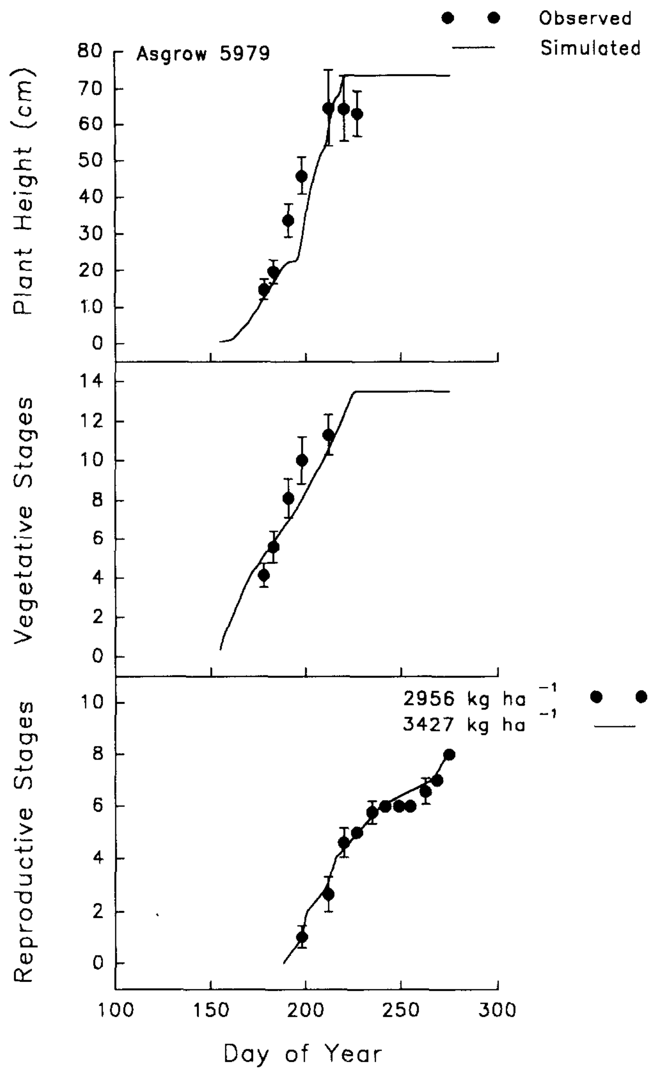

Fig. 6. Comparison of simulated and observed seasonal development of plant height and vegetative and reproductive stages for soybean cultivar Asgrow 5979 grown in Sharkey silty clay loam soil in the Mississippi Delta.

PDMH:	Potential rate of change in mainstem height (cm)
PDMW:	Potential rate of change in mainstem dry weight (g plant^{-1})
PDPLM(I):	Potential rate of change in length of mainstem petiole to leaf (cm hr^{-1})
PDPWM(I):	Potential rate of change in dry weight of mainstem petiole to leaf (g hr^{-1})
PDR:	Potential rate of change in RSTAGE (RSTAGES hr^{-1})
PDV:	Potential rate of change in vegetative stage of growth (VSTAGES hr^{-1})
PDWR(L, K):	Potential rate of increase of root dry weight in soil cell L, K (g hr^{-1})
PERIOD:	Length of calculation period under consideration (hr)
PHOTO:	Effective photoperiod for soybeans (hr)

RGCF(L, K):	Proportional reduction of root growth from all physical causes in soil cell L, K
RLEAF:	Number of trifoliolate leaves that appear on the mainstem between R0 and R1
RSTAGE:	Reproductive growth stage
RTWT(L, K):	Dry weight of root in soil cell L, K (g)
SDFILL:	Proportion of maximum seed weight obtained
SGTLI:	Proportion of shoot growing time lost temporarily while turgor is decreasing
SLOW:	Variable used to reduce growth of vegetative organs after flowering
TAIRL:	Air temperature (°C)
VSTAGE:	Vegetative growth stage
VSTMAX:	Maximum number of trifoliolate nodes on mainstem of determinate soybean plants

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